Optical Fibre Embedded in a Composite Laminated with Applications to Sensing

O. Frazão[1], N. Correia[2], C. Novo[2], A. Vieira[2], A. N. Costa[2], F. M. Araújo[3,1], and A. T. Marques[2]

[1] INESC Porto – Unidade de Optoelectrónica e Sistemas Electrónicos,
Rua Campo Alegre, 687, 4169 – 007 Porto, Portugal,
Tel.: +351 226 082 601; Fax: +351 226 082 799. Email: ofrazao@goe.fc.up.pt

[2] INEGI – Instituto de Engenharia Mecânica e Gestão Industrial,
Rua do Barroco, 174, 4465-591 Leça do Balio, Portugal,
Tel.: +351 229 578 713; Fax: +351 229 537 352.

[3] Departamento de Física da Faculdade de Ciências da Universidade do Porto,
Rua Campo Alegre, 687, 4169 – 007 Porto, Portugal,
Tel.: +351 226 082 601; Fax: +351 226 082 799.

Abstract

A smart sensor was fabricated using a carbon-epoxy composite laminate in which fibre Bragg gratings were embedded. These instrumented carbon fibre laminates can be used for reinforcement and protection of concrete/metallic structures, playing an important role in monitoring repaired or reinforced constructions.

1. Introduction

Fibre Bragg grating sensors (FBG) can be very useful in applications where layered materials, such as composites, are involved, because they provide a basis for the development of smart structures. These sensors allow measurement of parameters such as load/strain, vibration, temperature and detection of cracks and delamination phenomena tests [1], which are chiefly related with the monitoring of concrete loading/failure behaviour. Based on these properties we have conducted experiments by adhesively bonding smart sensors onto polymeric concrete samples, which where then submitted to standard loading tests. The work performed was aimed at the evaluation of stiffness and detection of fissures in carbon reinforced concrete, both through experimental tests and development of analytical models. Because of the recent interest in repairing metallic/concrete structures with composite laminates, it is safe to assume that such applications will be an appealing field for FBG sensors, since these are cases where monitoring is extremely important.

2. FBG Theory

An FBG is a periodic modulation of the refractive index of the core of a single mode optical fibre, written by exposure to UV light in the region around 248nm [2]. This fabrication process is based on the photosensitive mechanism, which is observed in Ge-doped optical fibres [3]. If broadband light is travelling through an optical fibre containing such a periodic structure, its diffractive properties promote that a very narrow wavelength band is reflected back. The centre wavelength of this band can be represented by well known the Bragg condition:

$$\lambda_B = 2n_{eff}\Lambda , \tag{1}$$

where λ_B is the centre wavelength, n_{eff} is the effective index of the guided mode and Λ is the period of the index modulation. The FBG ressonance wavelength will vary accordingly with temperature or strain changes experienced by the fibre. For a temperature change ΔT, the corresponding wavelength shift is given by:

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n}\frac{\partial n}{\partial T}\right)\Delta T = \lambda_B(\alpha + \xi)\Delta T , \tag{2}$$

where α is the fibre thermal-expansion coefficient, and ξ is the fibre thermo-optic coefficient. The wavelength shift, induced by a longitudinal strain variation $\Delta\varepsilon$ is given by,

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial \varepsilon} + \frac{1}{n}\frac{\partial n}{\partial \varepsilon}\right)\Delta\varepsilon = \lambda_B(1 - p_e)\Delta\varepsilon , \tag{3}$$

where p_e is the photoelastic coefficient of the fibre. For a silica fibre, the wavelength-strain and wavelength-temperature sensitivities are ~13pm°C^{-1} and ~1.15pm$\mu\varepsilon^{-1}$, for a Bragg wavelength centred at 1555nm [4].

3. Smart Sensors Plate Fabrication and Characterization

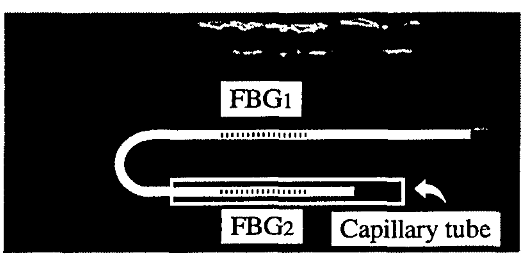

Fig. 1 Smart sensor plate with illustration of FBG sensor placement.

Two fibre Bragg gratings were embedded between layers of pre-impregnated carbon fibre/epoxy resin to produce a smart sensor plate. The laminate had three layers with dimensions of 150x70x1mm^3 and was cured inside an autoclave at 100°C during 1 hour with 0.8x10^{5}Pa pressure. The FBG_1 (λ_{B1}=1539nm) was used for measuring strain and temperature, while the FBG_2 (λ_{B2}=1530nm) was only sensitive to temperature. The FBG_2 sensor was properly isolated from strain inside a steel capillary tube with $\varnothing_{ext}$=0.8 mm, $\varnothing_{int}$=0.5mm and length L=40mm. The characterization of the smart sensor consisted in temperature measurements holding strain constant (ε=0) and strain measurements with constant temperature (T=20°C). Fig. 2-a) and 2-b) show the response of the two FBGs to temperature variation under constant strain and bending strain variation at constant temperature, respectively.

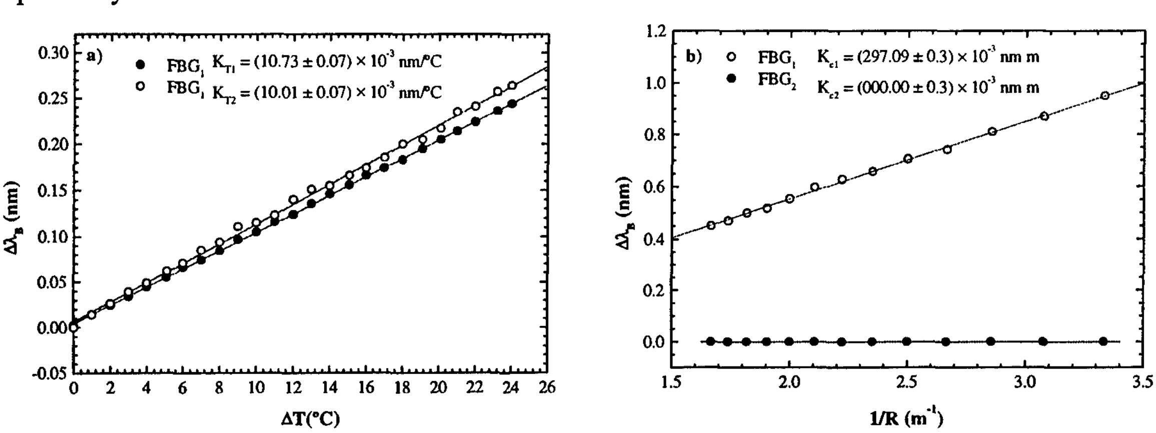

Fig. 2 Response of smart sensor plate to: **a)** Temperature; **b)** Inverse curvature radius (1/R).

As expected different sensitivities were obtained for strain, while similar ones were obtained for temperature. The small difference observed between the thermal sensitivities can be attributed mainly to the additional strain effect of the material's thermal expansion. Monitoring both Bragg grating wavelengths allow us to determine simultaneous temperature and bending strain. In fact, from data contained in Fig. 2 the following relationship can be expressed:

$$\begin{bmatrix} \Delta T \\ \Delta C \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} K_{C2} & -K_{C1} \\ -K_{T2} & K_{T1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} = -336.3 \begin{bmatrix} 0.0000 & -297.09 \\ -10.01 & 10.73 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix}, \tag{4}$$

where $\Delta = K_{T1}K_{c2} - K_{c1}K_{T2}$, ΔT and ΔC are temperature and curvature variations. Based on this equation and from the experimental evaluation of $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ we are then able to determine both ΔT and ΔC.

4. Experimental Results

Experiments were conducted on instrumented and/or reinforced polymer concrete plates, with dimensions of $600\times100\times20mm^3$, using a test machine INSTRON Universal (mod. 4208). All three point bending tests performed had a span length of 500mm. Fig. 3 shows two types of plates tested. In a Fig. 3-a) we can observe a CFRP (Carbon Fibre Reinforced Polymer) concrete plate. The CFRP was used to increase the tension strength and reduce the crack propagation rate of the plate, and it contained 3 FBG sensors. One was located at the centre and the others two at 150mm to each side. In Fig. 3-b) it is shown a concrete plate instrumented with the smart sensor plate described in the previous section.

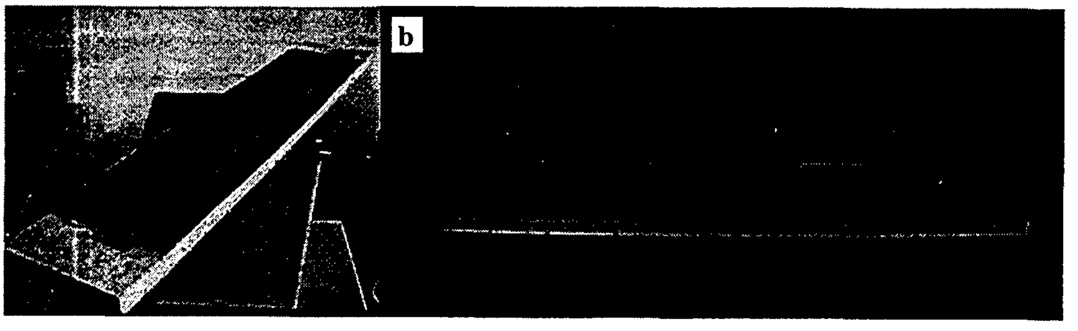

Fig. 3 a) CFRP reinforced concrete plate containing FBG sensors, and **b)** smart sensor plate adhesively bonded to polymer concrete plate.

The system used for monitoring the smart sensor plates is presented in Fig. 4. The system included an OSA – optical spectrum analyser (ANDO AQ 6330), an EBOS – erbium broadband optical source (PHOTONETICS), a 3 dB coupler and a computer data acquisition system.

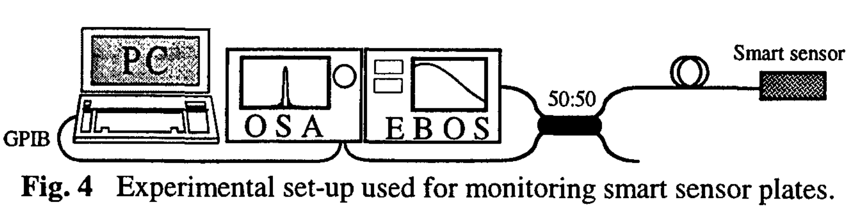

Fig. 4 Experimental set-up used for monitoring smart sensor plates.

Fig. 5-a) and 5-b) show test results of reinforced and non-reinforced polymer concrete plates (strain vs. time). The temperature evolution measured through the sensor FBG_2 during the test, in the smart sensor plate is also presented. The non-reinforced concrete plate showed no cracking before failure and presented an ultimate strain of 280με at the sensor location (see Fig. 5-a). The reinforced concrete plate, on the other hand, endured a much higher strain (about 7×) and failed in compression developing 4 compression cracks. The FBG monitoring system also allowed the detection of these

cracks as can be observed in peak (1) of Fig. 5-b) – here (2) denotes a failure of sensors 1 and 3 due rupture of the optical fibre containing FBG sensors. The crack detection is shown in detail in Fig. 6 using data extracted from the peak (1) in Fig. 5-a).

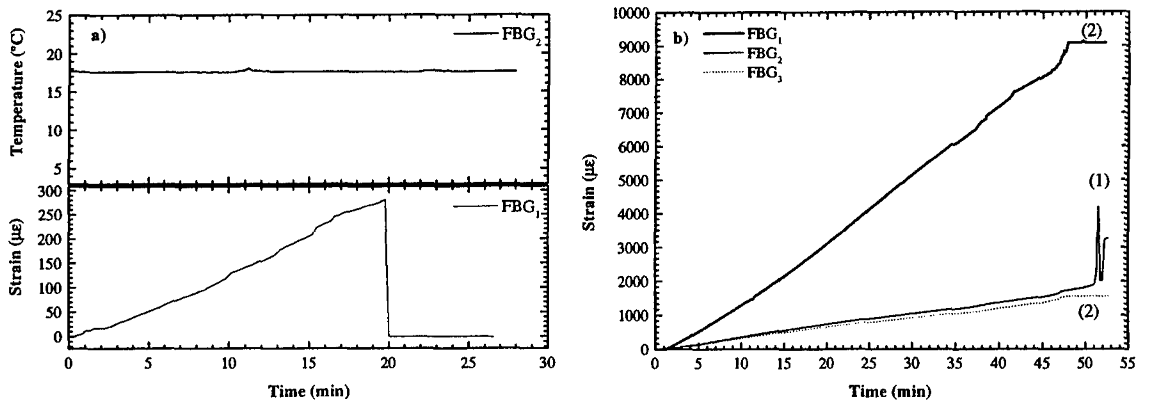

Fig. 5 Test results of the strain and temperature evolution of the: **a)** Non-reinforced concrete plate; **b)** Reinforced concrete plate containing 3 FBG sensors.

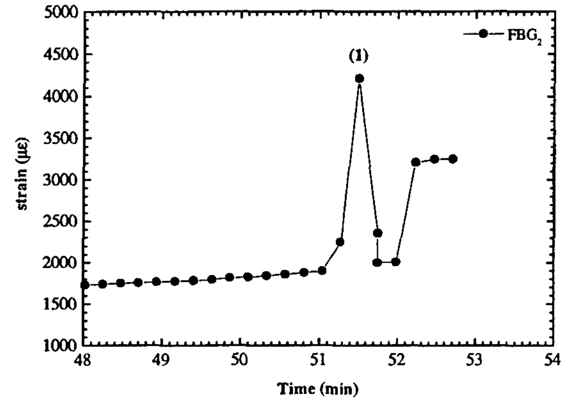

Fig. 6 Detail of crack detection and final failure extracted from peak (1) in Fig. 5-a).

5. Conclusion

FBG sensors showed the ability to detect strain and cracks in concrete plates. A 1mm thick CFRP laminate reinforcement allowed an increase of 7 times in strain and induced compressive cracking in the concrete polymer. The monitoring system failed when the optical fibres were forced to endure strain values in excess of 9000$\mu\varepsilon$, causing signal loss due to rupture of the optical fibres. The possibility of using fibre optic instrumented plates in rehabilitation of civil structures was demonstrated, since strain measurements and compressive cracking can be effectively detected.

References

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, "Fiber grating sensors", *J. Lightwave Technol.* vol. 15, pp. 1442-1463, 1997.

[2] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask", *Appl. Phys. Lett.*, Vol. 62, pp. 1035-1037, 1993.

[3] K. O. Hill, B. Malo, F. Bilodeau, and D. C. Johnson, "Photosensitivity in optical fibers", *Annu. Rev. Mater. Sci.* vol., 23, pp. 125-157, 1993.

[4] W. W. Morey, G. Meltz, and W. H. Glenn, "Fibre optic bragg grating sensors", in *Fiber Optic and Laser Sensors VII*, in Proc. SPIE 1169, Boston, USA, pp. 98-107, 1989.